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A plant-specific bottom-up approach for assessing the cost-effective energy conservation potential and its ability to compensate rising energy-related costs in the German iron and steel industry

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HIGHLIGHTS

- Methodology includes the efficiency of single plants and the complexity of measures.
- Energy conservation cost curves for process and plant system boundaries.
- Economic conservation potential: 11.7% fuel, 2.2% electricity and 12.2% CO_2.
- EAF route: economic measures can compensate 50% higher electricity prices.
- BOF route: average energy costs will rise by 6–13% during 2013–2035.

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ABSTRACT

Germany produces more steel than any other European country (42.7 Mt steel in 2012). The steel production accounts for 22% of Germany's final industrial energy consumption. We assessed the potential of 32 identified energy conservation measures by deriving fuel, electricity and CO_2 conservation cost curves. We developed a methodology which respects the current efficiency of individual plants and two different system boundaries: a process boundary for benchmarking measures and a facility boundary for calculating the total energy conservation potential. With moderate electricity and carbon price developments for the investigation period 2013–2035, the cost-effective conservation potentials are estimated to be 11.7% for fuel, 2.2% for electricity and 12.2% for fuel and process-related CO_2 emissions compared to the industry's final energy use and CO_2 emissions in 2012. For the sensitivity analysis, we varied electricity and carbon prices and our results showed that adopting cost-effective energy conservation measures can compensate for rising energy prices but the extent differs between the production routes. While the EAF route could compensate up to 50% higher electricity prices, the options for the BF/BOF route to reduce the fossil fuel consumption are limited. Thus, the energy-related production costs of the BF/BOF route increased in average by 6–13% between 2013 and 2035.

1. Introduction

Industrial production processes are responsible for 28% of the final energy used globally and 32% of energy-related CO_2 emissions (IEA, 2012). One of the most energy-intensive industrial processes is the production of iron and steel. The German iron and steel industry was the second largest industrial energy consumer in Germany in 2010 with a share of 22% (786 PJ) (cf. DESTATIS, 2010) and is responsible for 7.5% of the country's CO_2 emissions (cf. VDEh, 2012). Germany, with more than 40 Mt steel p. a., is the largest steel producer in Europe and ranks seventh worldwide (VDEh, 2012). As is typical for an energy-intensive industry, energy costs represent a large part (36%) of the gross added-value (Frondel and Grösche, 2010). The efficient utilisation of energy resources can, therefore, be a decisive competitive factor, especially for companies operating on the global market. Accordingly, steel works' concern for energy efficiency dates back long before this term became omnipresent in energy policies.[1] With the

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[1] We define energy efficiency as the specific energy consumption level which achieves the desired output level with the lowest costs. Hereby, the term "costs" includes the costs for the utilisation of resources plus external costs, e.g. air pollution, anthropogenic climate change (cf. Blesl and Kessler, 2013). In this context, an energy conservation measure that reduces the specific energy-intensity of an energy service is not implied to be energy-efficient.

beginning of the year 2013 and the next phase of the European Union Emission Trading Scheme (EU ETS), German steel works are facing increasing burdens in form of rising energy taxes, cost apportionments based on the German Renewable Energy Act (EEG) and CO_2 allowance costs, so that more and more steel works are questioning Germany as a production location (Harste and Lüngen, 2011).

Adapting cost curves to display measure-specific energy conservation potentials in an economic framework is a common method to provide a quantitative basis for the discussion about industrial energy efficiency. Examples are the CSC (Conservation Supply Curve) concept from Lawrence Berkeley National Laboratory which has been performed for the Chinese iron and steel industry (cf. Hasanbeigi et al., 2013a), the Chinese cement industry (cf. Hasanbeigi et al., 2013b) and for motors systems in the U.S. (cf. McKane and Hasanbeigi, 2011). McKinsey used cost curves to display Greenhouse gas abatement opportunities to support the discussion about what actions would be most effective in delivering emissions reductions (McKinsey, 2009). Energy conservation cost curves (ECCC) allow to benchmark individual measures as well as the whole industry on an international level. This knowledge can help in identifying potentials for companies and policy makers likewise (Farla and Block, 2001). Due to the economic perspective, the additional burdens of energy-intensity reduction targets can be displayed in the cost curve and transparently communicated to policy makers.

In this article, we first present the two system boundaries of the investigation followed by the developed calculation method for the cost curves. We then provide a consistent list of energy conservation measures applicable to the German iron steel industry. Measures that respect the present energy-intensity by plant-specific values are explained separately. We divide the discussion of the cost curves into fuel (FCCC) and electricity conservation cost curves (ECCC). Here, we discuss both cost curves first on the process level to benchmark individual measures and second on the facility level to derive the total conservation potential. Lastly, in the sensitivity analysis, we outline the impacts of varying electricity, carbon prices and interest rates on the cost-effective conservation potentials and on the final energy-related production costs.

2. Method

2.1. System boundaries

The importance of defining the system boundary has been highlighted by several studies (e.g. Tanaka, 2012, 2008; Siitonen et al., 2010; IEA, 2007). It is stressed that different definitions of system boundaries will lead to varying results. Thus, comparison of studies with deviating system boundaries should only be carried out carefully or better be avoided (Tanaka, 2012). In the case of the iron and steel industry, the high integrity of the production processes increases the need for thoroughly defined system boundaries. Further, CSPA (2007) notes that process and facility boundaries are not necessarily the same. In the following investigation those two boundaries are therefore distinguished.

2.1.1. Process and facility boundary

The process boundary covers each process and its respective measure individually (see Fig. 1). It displays the energy conservation potential of individual measures and is therefore suitable for benchmarking the investigated measures. At the same time, the process boundary does not respect the effect of competing measures, e.g. measures that utilise the same waste heat or achieve energy conservations with the same principle (e.g. the substitution of reducing agents (see Table 1)), which forbids the addition of the energy conservations of these measures. In order to quantify the energy conservation potential for one facility and the whole industry in the end, we respect a second boundary, i.e. the facility boundary, in the investigation (see Fig. 1).

2.1.2. Measures

First of all, only measures are respected that are commercially available or about to reach market maturity in the foreseeable future and result in a reduction of the fuel or electricity utilisation. In terms of prospective future technologies, we analysed the four measures proposed by the ULCOS (Ultra-Low CO_2 Steelmaking) project (cf. Meijer et al., 2009). We decided to respect the Top Gas Recovery Blast Furnace (cf. Hirsch et al., 2012) without carbon capture and storage (CCS) in the investigation since the remaining measures are not expected to be around before 2030 (cf. Pardo and Moya, 2013). Further, measures that are based on process substitution (e.g. higher ratio of electrical steel to oxygen steel production), renewable energies (except biochar), CCS-technologies in general and cross-sectional technologies (e.g. energy efficient electrical motors) or measures that are clearly uneconomical are excluded.

2.1.3. Ceteris paribus

Lastly, the investigation is carried out ceteris paribus. The total production capacity is hard linked to the investigated steel plants. The demand of the different steel products is based on the year 2011 (cf. VDEh, 2012) and held constant. The constant production capacity and demand restrict, among others, the adoption potential of measures that are restricted to certain kinds of steel products e.g. the near net shape casting technologies thin slab and strip casting (see Table 1).

2.2. Data collection

The parameters of the measures, e.g. specific energy conservations and costs (see Table 1), were taken as a first step from international studies on energy or CO_2 conservation measures in the iron and steel industry (cf. Hasanbeigi et al., 2013a; Johansson and Söderström, 2011; Guo and Fu, 2010; US-EPA, 2010; Worrell et al, 2010; van Wortswinkel and Nijs, 2010; Xu and Da-qiang, 2010; Bettinger et al., 2009; NEDO, 2008; Ribbenhed et al., 2008; JCI, 2007; Oda et al., 2007; de Beer et al., 1998) and challenged with the literature that focus on Europe (cf. Pardo and Moya, 2013; Dahlmann et al., 2012; EIPPCB, 2012) or Germany in particular (cf. Schlomann et al., 2011; Dahlmann et al., 2010; Bender et al., 2008; Aichinger and Steffen, 2006). Where available, individual measures were further elaborated with publications by the German trade journal “stahl und eisen”[2] (see Table 1). The results were discussed with experts of the Steel Institute VDEh of the German Steel Federation and the Fraunhofer Institute for Systems and Innovation Research ISI. Where necessary, capital and operational costs were converted into EUR_{2013} and adapted to Germany with factors for location and cost index from Intratec (2013).

In terms of plant data, a first version of the as-built model was created on the basis of the information available from the Steel Institute VDEh (e.g. VDEh, 2012) and from individual steel works (e.g. annual reports, environmental reports). The data could then be complemented in a second step with the Steel Institute VDEh′s Plantfacts database (cf. VDEh, 2011). This database is continuously feed and updated from the information available by publications in the abovementioned journal “stahl und eisen”. In case of Germany, the data of the steel plants are based on over 250 unique

[2] The journal “stahl und eisen” is focussed on the production and processing of iron and steel and is published since 1881 by the Steel Institute VDEh.

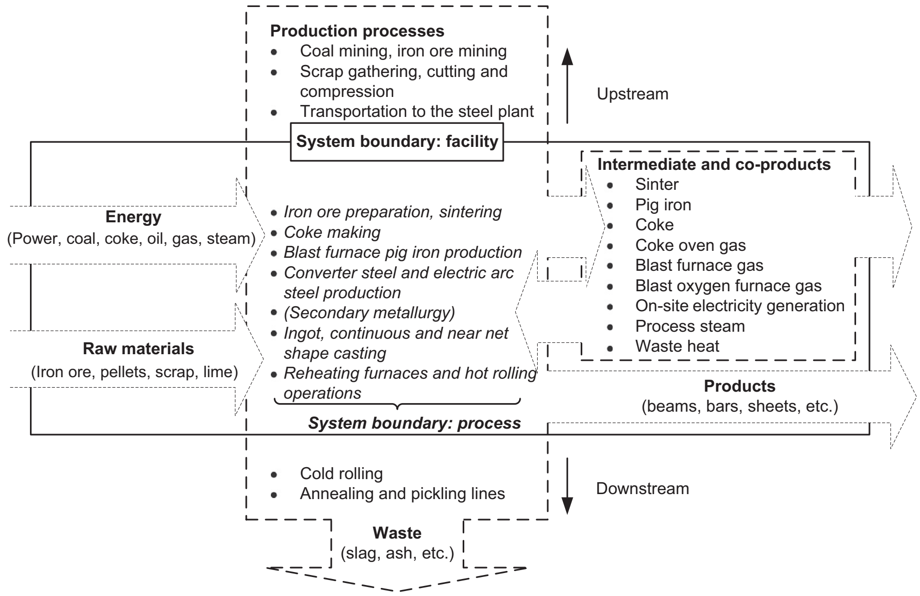


Fig. 1. Typical production processes in the iron and steel industry and the two system boundaries respected in the investigation.

publications. The final as-built model contains plant-related identification data, i.e. company, type, works, location, and plant-specific data, e.g. year of construction and last modernisation, manufacturer, operation condition, design capacity and output.

The parameter analysis provides another necessary foundation for the calculation. While parameters that are respected in the sensitivity analysis are explicitly addressed in Section 4.3.1, Fig. 2 shows the basic energy and CO_2 certificate prices which are mainly based on Schlomann et al. (2011) except for electricity. It needs to be noted that the CO_2 certificate price for the year 2013 does with 11.50 EUR/t CO_2 not reflect the current price of the European Energy Exchange (EEX). However, we refrained from adapting the starting price in order to maintain the initial price development and thus the comparableness. The electricity price is adapted to the German steel sector (see Section 4.3.1) by combining the data from Seefeld et al. (2007) with the trend forecast of Fahl et al. (2010).

2.3. Calculation of energy conservation cost curves

For the comparability of the results, the definition of the calculation method is as important as the definition of the system boundary (cf. Tanaka, 2012). The calculation of energy conservation cost curves (ECCC) can be divided into several steps (see Fig. 3). Hereby, the order of the first two steps (i.e. identification of energy conservation measures and building the as-built plant model) are determined by the fact that the energy conservation measures specify the data structure of the as-built plant model. After data processing and consistency checks, the ECCC can be calculated. This step can be further subdivided into the calculation of the energy conservation potential (see Section 2.3.1) and the energy conservation costs (see Section 2.3.2). Then, first ECCC on process level (see Fig. 1) can be drawn and sensitivity analyses be performed. However, in order to be able to derive conclusions on the total energy conservation potential of the industrial sector, the system boundaries need to be broadened to cover the whole facility (see Fig. 1) so that the issue of competing measures is respected (see Section 2.1). Following the theory of neoclassical economics – actors maximise their individual profits – the measure with the highest net present value (NPV) is adopted. This ranking is carried out for all measure at each plant individually. Inevitably, the measure-specific energy-conservation potentials on facility level will be lower than the ones on process level. When the ECCC on facility level are obtained, sensitivity analysis can be carried out (see Section 4.3). After each parameter variation, the measures need to be ranked again.

2.3.1. Calculation of the energy conservation potential

The energy conservation potential $ESav_{k,i}$ for a measure k is calculated for each plant i individually. In a first step, the respective requirements for the applicability of measure k to plant i are checked. The requirements for the implementation are:

- Measure k is not applied to plant i yet .
- Plant i condition status is operational.
- Plant i will not be shut down within the next three years.
- Plant i fulfils the measure-specific technical requirements, e.g. sufficient top gas pressure (see Table 1).

If all four requirements are met, the calculation is further separated into two cases: measures with plant-unrelated specific energy conservations and measures with plant-related specific energy conservations. In the first case, energy conservations $ESav_{k,i}$ of measure k at plant i are determined by the product of the specific fuel $FlSav_k$ and electricity conservations $ElSav_k$ and the annual capacity Cap_i

$$ESav_{k,i} = ((FlSav_k + ElSav_k) \times Cap_i).$$

In case of measures with plant-related specific conservations, $ESav_{k,i}$ is based on the difference between the maximal $X_{max,k}$ and the present plant-specific value $X_{i,k}$ (e.g. present pulverised coal injection rate (see Table 1)) multiplied by a conversion factor Y_k and the annual capacity Cap_i of plant i

$$ESav_{k,i} = ((X_{max,k} - X_{k,i}) \times Y_k \times Cap_i).$$

The total energy conservation potential $ESav_k$ of a measure k results from the sum of the individual conservations $ESav_{k,i}$. The abatement of CO_2 emissions are calculated analogously.

2.3.2. Calculation of the energy conservation costs

The calculation of the marginal energy conservation costs $MECC_k$ is divided into three steps:

The first step is the plant-specific determination of the net present value $NPV_{k,i}$ of measure k which is the result of the sum of

Table 1
Characterisation of the investigated energy conservation measures and their applicability to the German iron and steel industry.

ID	Name	Retrofit (R) / Substitute (S)	Electricity conservations [MJ/t product]	Fuel conservations [MJ/t product]	CO_2 abatements [kg CO_2/t p. a.]	CAPEX [EUR_{2013}/t p. a.]	OPEX [EUR_{2013}/t p. a.] [d]	Measure lifetime [a]	Intertwining factor	Requirements for application [e]	Competing measures	Applicable to [# plants of # total plants]	Applicable capacity [kt p. a.]	Sources and further literature
Sinter plant														
SINT1	Waste heat recovery from cooler [b]	R	–	54	6.97	4.45	–	10	0.5	Rotary cooler at sinter plant	SINT*	6 of 9	9890	Hasanbeigi et al. (2013a), JASE-W (2012), US-EPA (2010)
SINT2	Improved waste heat recovery from exhaust gas [a]	R	38 [1]	51	6.58	5.11	–	20	0.5	–	SINT*	8 of 9	25,065	US-EPA (2010), JCI (2007)
SINT3	Partial gas recirculation (LEEP)	R	−10	213	27.48	9.89	–	20	0.5	–	SINT*	8 of 9	25,065	EIPPCB (2010)
SINT4	Selective gas recirculation (EPOSINT)	R	–	124	15.96	6.84	–	20	0.5	–	SINT*	8 of 9	25,065	Reidetschläger et al. (2012), EIPPCB (2010)
Coke plant														
Coke1	Extended COG recovery [b]	R	0	var. [2]	var. [3]	5.67	–	20	0.5	Recovery rate below 484 m^3 COG/t coke	–	3 of 5	4,740	US-EPA (2010), Liszio (2003), US-EPA (2000)
Coke2	Coke Dry Quenching (CDQ)	R	550 [1]	–	27.50	92.51	0.65	18	0.2	–	–	5 of 5	9,700	Hasanbeigi et al. (2013a), Liszio et al. (2012), US-EPA (2010), EIPPCB (2009), NEDO (2008), JCI (2007), Bisio and Rubatto (2000)
Coke3	Coke Stabilization Quenching (CSQ)	R	–	102	0.01	2.85 [4]	–	20	0.5	–	–	3 of 5	4,740	EIPPCB (2010), Liszio et al. (2012)
Blast furnace														
BF1	Extended Pulverised Coal Injection (PCI) [b]	R	–	var. [2]	var. [3]	8.81	–	20	0.5	Injection rate below 250 kg coal/t iron	BF6	13 of 16	26,330	EIPPCB (2010), Worrell et al. (2010), Ribbenhed et al. (2008), JCI (2007)
BF2	Extended blast furnace gas recovery [b]	R	–	66	6.93	0.51	–	15	0.8	Twin bell top charging system	BF5	2 of 16	3,000	Hasanbeigi et al. (2013a), US-EPA (2010)
BF3	Top gas recovery turbine (TRT)	R	200	–	0.00	7.01	–	15	0.5	Top gas pressure above 2.5 bar	–	6 of 16	10,930	Hasanbeigi et al. (2013a), Xu and Da-qiang (2010), NEDO (2008), Oda et al. (2007), IEA (2007)
BF4	Slag heat recovery [a]	R	–	350	19.60	1.08 [5]	–	20	0.5	–	–	14 of 16	30,630	EIPPCB (2010), Schlomann et al. (2011), Xie (2010), MetSoc (2010)
BF5	Top Gas Recovery Blast Furnace (TGRBF) [a]	S	–	900 [6]	116.10	110.29	–	20	0.6	–	BF2	14 of 16	30,630	Hirsch et al. (2012), EC (2010), Meijer et al. (2009)
BF6	Biochar as reducing agent [a]	R	–	569	382 [7]	–	15.08	20	–	Annual capacity above 2000 kt p. a.	BF1	10 of 16	26,400	Mathieson et al. (2011), Babich et al. (2010), Norgate and Langberg (2009)

Basic oxygen furnace														
BOF1	Basic oxygen furnace gas recovery	R	–	750	49.41	37.42	–	10	0.5	–	–	8 of 21	16,110	Arens et al. (2012), US-EPA (2010), Marion (2009), IEA (2007)
BOF2	Improved process monitoring and control [b]	R	18	–	–	0.61	–	20	0.5	–	–	16 of 21	28,360	Kleimt et al. (2012), US-EPA (2010), Zuliani et al. (2009), Bender et al. (2008)
Electric arc furnace														
EAF1	Improved foamy slag control [b]	R	41	65	6.10	3.37	–	20	0.2	No impact sound-based monitoring, e.g. foamy slag manager (FSM)	EAF8	19 of 26	9,250	Bandusch et al. (2012), Lech-Stahlwerke (2012), US-EPA (2010), Reichel et al. (2009), Fandrich et al. (2009)
EAF2	Bottom stirring	R	70	–	–	1.02	–	20	0.8	–	EAF8	14 of 26	10,260	US-EPA (2010), Kirschen et al. (2009)
EAF3	High-performance transformer (205 MVA)	R	var. [2]	–	–	5.85	–	30	–	Transformer power below 205 MVA	EAF8	22 of 26	13,700	Hölling et al. (2011), Worrell et al. (2010)
EAF4	Direct Current (DC) Arc Furnace	R	320	0	–	6.64	–	20	0.5	Annual capacity above 500 kt p. a.	EAF6; EAF8	14 of 26	11,370	Dahlmann et al. (2012), US-EPA (2010)
EAF5	Evaporative cooler	R	–	193	–	15.42	–	20	0.8	Annual capacity above 300 kt p. a.	EAF6;EAF8	18 of 26	13,020	Kleimt et al. (2012), Hollands et al. (2011), JASE-W (2011), Risonarta et al. (2011), Schliephake et al. (2011), tenova (2011), Hollands et al. (2011), Born and Grandrath (2010)
EAF6	Continuous charging and scrap preheating (CONSTEEL®)	R	220	–	–	8.48	−2.49	20	0.8	–	EAF5; EAF8	23 of 26	13,700	Bandusch et al. (2012), Memoli et al. (2012), Toulouevski and Zinurov (2010), US-EPA (2010), Memoli et al. (2009), Born and Grandrath (2010)
EAF7	Process optimization using fuzzy logic [a]	R	108	–	–	1.63	−0.83	20	0.2	–	EAF8	23 of 26	13,700	APP (2010), US-EPA (2010), Zuliani et al. (2009), Bender et al. (2008)
EAF8	Continuous operation and heat recovery with Arccess Steady EAF [a]	S	248	–	–	117 [8]	–	20	1.0	–	EAF*	11 of 26	8,440	Sagermann (2012)
Casting														
CC1	Thin slab casting	S	–	1050	58.80	117.24	–	20	0.2	Annual capacity above 1500 kt p. a. Cumulative capacity must not exceed 19,000 kt p. a.	ROLL*	8 of 19	19,000	Schmidt-Jürgensen (2010), Dahlmann et al. (2010), US-EPA (2010), Diemer et al. (2007)
CC2	Strip casting [a]	S	–	1690	94.64	95.64	–	20	0.2	Cumulative capacity must not exceed 1000 kt p. a.	ROLL*	–	900	Woidasky et al. (2012), Geibler et al. (2011), Schmidt-Jürgensen (2010), Dahlmann et al. (2010), Kämpfer (2009)
Rolling mill														
MILL1	Regenerative burners	R	–	408	22.85	5.92	–	10	0.5	–	CC*	26 of 32	34,585	BSW (2011), Irretier (2010), US-EPA (2010), Marion et al. (2008), NEDO (2008)
MILL2	Recuperative burners [b]	R	–	378	21.17	4.24	–	10	0.5	–	MILL1; CC*	10 of 32	8,995	

Table 1 (*continued*)

ID	Name	Retrofit (R) / Substitute (S)	Electricity conservations [MJ/t product]	Fuel conservations [MJ/t product]	CO_2 abatements [kg CO_2/t p. a.]	CAPEX [EUR_{2013}/ t p. a.]	OPEX [EUR_{2013}/ t p. a.] [d]	Measure lifetime [a]	Intertwining factor	Requirements for application [e]	Competing measures	Applicable to [# plants of # total plants]	Applicable capacity [kt p. a.]	Sources and further literature
														Irretier (2010), US-EPA (2010), Worrell et al. (2010).(Marion et al. (2008), Aichinger (2007)
MILL3	Hot charging [b]	R	–	560	31.36	25.56	–	20	0.1	Charge temperature below 300 °C	CC*	19 of 32	21,575	US-EPA (2010), Dahlmann et al. (2010), Sheikhi et al. (2009), NEDO (2008)
MILL4	Improved isolation [b]	R	–	160	8.96	16.97	–	20	1.0	–	CC*	27 of 32	28,405	Irretier (2010), US-EPA (2010)
MILL5	Flameless OxyFuel burners	R	–	396	22.18	4.24 [9]	–	20	0.5	–	CC*	25 of 32	17,505	US-EPA (2010), von Schéele et al. (2008) Praxair (2007), Milani and Saponaro (2001), Wünning (1991)
MILL6	Heat recovery from cooling water	R	–	30	1.68	1.41	–	15	0.5	–	CC*	28 of 32	38,555	(Feralpi Stahl (2011), Johansson and Söderström (2011), Worrell et al. (2010), Deutsche Edelstahlwerke (2009)
On-site power plants														
PP1	Renewal of on-site power plants	S	var.	var.[2]	var. [3]	130.26	–	35	–	–	–	3 of 7	–	Schlomann et al. (2011), Bock and Schmidt (2008), Weishar (2008), Diemer et al. (2007)

* Applies to all measures of the same production process.

[a] Based on the prerequisite that the measure is commercially available in 2013.

[b] Information of some plants, which is necessary to validate the applicability of the respective measure, is partly based on assumptions.

[c] Only direct CO_2 emissions, i.e. fuel and process-related CO_2 emissions, are accounted for.

[d] Change in the annual operations & maintenance expenditures such as increased maintenance cycles or additional need of chemicals.

[e] Additional requirements for the adoption that go beyond the standard requirements (see Section 2.3).

[1] The steam that is typically recovered by the respective measure is converted to electricity with the average efficiency of German on-site power plants (30% Rubel et al., 2009) in order to reflect the effects of varying electricity prices in the sensitivity analysis.

[2] The energy conservations are calculated plant-specifically (see Section 3).

[3] The CO_2 abatements are depending on the actual fuel conservation of each plant. The specific CO_2 emissions for the conversion are: 0.0946 t CO_2/ GJ coal, 0.0561 t CO_2/GJ natural gas, 0.129 t CO_2/ GJ coke, 0.0774 t CO_2/GJ fuel oil (cf. Quaschning, 2011), 0.048 t CO_2/GJ COG (cf. Bender et al., 2008) and 0.105 t CO_2/GJ BFG (cf. UBA, 2003).

[4] Although CSQ is installed in two German coke plants, there is no cost data available. The process step scoring method (cf. Taylor, 1977) with parameters based on Liszio et al. (2012) has been used to get a rough estimation of capital costs. Through discussions with the Steel Institute VDEh, it was known that the capital costs of CSQ are substantially lower than the capital cost of CDQ.

[5] Although this measure has been investigated for over the last three decades, a commercial application is yet not available. The heat recovery of EAF slag in pilot project in Canada is reported to have capital costs around 2.5 CAD/GJ (cf. MetSoc, 2010) which are adapted to Germany.

[6] Through the recirculation of the top gas, a reduction of the specific coke consumption by 39% is expected (Hirsch et al., 2012; EC, 2010). A specific coke consumption of 10.18 GJ/t iron (cf. Arens et al., 2012) would lead to specific savings of 3.97 GJ/t iron. At same time, ca. 80% of the blast furnace gas is no longer available for other applications which needs to be respected on facility level. The net specific energy conservations are therefore assessed to be 0.9 GJ/t iron.

[7] It is assumed that biochar replaces the current coal injection rate of 137.8 kg coal/t iron (cf. Ghenda, 2011). As the biochar is produced from biomass the CO_2 emissions can be calculated as carbon neutral (cf. Babich et al., 2010; Xu and Da-qiang, 2010).

[8] The continuous operation leads to smaller plant dimension whilst having the same output. Thus, the cost for steel structure and foundation are decreased by 25% compared to a standard furnace (Sagermann, 2012).

[9] The capital costs are assumed to be on the same level as the cost for recuperative burners (cf. Milani and Saponaro, 2001).

the annual discounted cash flows $CF_{k,i,t}$

$$NPV_{k,i} = \sum_{t=t_{Start}}^{t_{End}} CF_{k,i,t} \times (1+r)^{-t+t_{Start}}$$

where r is the interest rate and t the year. $CF_{k,i,t}$ respects the cost reduction due to the reduced fuel consumption ($FlSav_k \times FlCost_t$), reduced electricity consumption ($ElSav_k \times ElCost_t$) and reduced costs for CO_2 certificates ($CSav_k \times CCost_t$), the non-energy and non-carbon-related change in operational expenditures $OPEX_k$ (e.g. increased or decreased maintenance costs) as well as the condition-based capital expenditure $CAPEX_{k,t}$

$$CF_{k,i,t} = (FlSav_k \times FlCost_t + ElSav_k \times ElCost_t + CSav_k \times CCost_t - OPEX_k + CAPEX_{k,t}) \times Cap_i$$

$CAPEX_{k,t}$ is further based on two cases: retrofit or rebuild. In the first case, it is assumed that measure k expands the existing plant i modularly. The ratio of the intertwining complexity between the measure k and the underlying plant i is expressed as the intertwining factor $\alpha_k \in \{0,1\}$. This factor was introduced in order to respect the fact that companies tend to postpone the adoption of energy conservation measures due to economical synergies until the modernisation or renewal of the plant is necessary. Besides, the intertwining factor takes into account that retrofitting an older plant is involved with additional risks. Thus, the costs for adopting a retrofit measure are increased as additional capital costs $CAPEX_k$ weighted with factor α_k are needed when the underlying plant needs to be modernised (see Fig. 4). For instance, retrofit measures that involve the implementation of heat exchangers or the modernisation of the process control system have a high intertwining factor (e.g. $\alpha_k \geq 0.5$) as they are specifically designed to the operation parameters of the respective plant (cf. Schliephake et al., 2011).

In the second case where the measure k replaces the plant i completely, the costs for the reference scenario (i.e. present plant is retained and needs to be modernised over time) are respected in $CAPEX_{k,t}$ (see Fig. 5). In contrast to the retrofit measures, the straight-line depreciation of both, measure k and the reference plant i, is credited to $CAPEX_{k,t}$ at the end of the investigated period t_{End}.

In the second step, the annuity factor $ANF_{r,m}$ is calculated which is needed to obtain the annualised capital costs. It is calculated as

$$ANF_{r,\,m} = \frac{(1+r)^m \times r}{(1+r)^m - 1}$$

where r is the interest rate and $m = t_{End} - t_{Start}$ the period of the investigation.

In the last step, the marginal energy conservation costs $MECC_{k,r,m}$ are obtained. Here the sum of the NPVs of all plants N is annualised with $ANF_{r,m}$ and divided by the sum of all energy

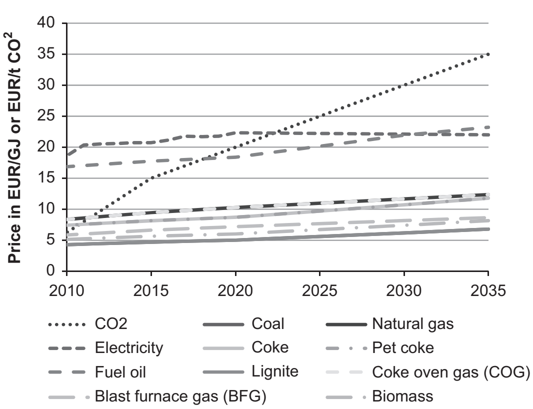


Fig. 2. Energy carrier and carbon price developments for the German iron and steel industry in investigated period 2013–2035.

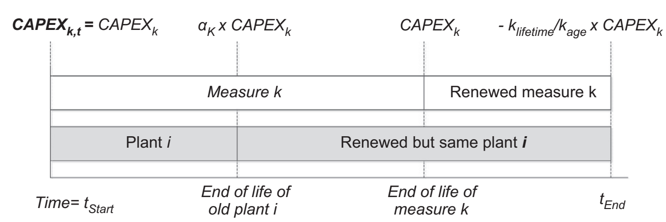


Fig. 4. The different states of the capital expenditure for a retrofit measure over the investigated period.

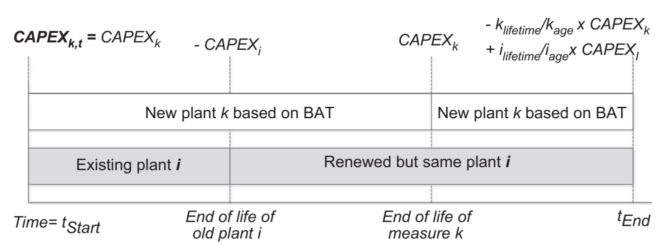


Fig. 5. The different states of the capital expenditure for a substitute measures over the investigated period.

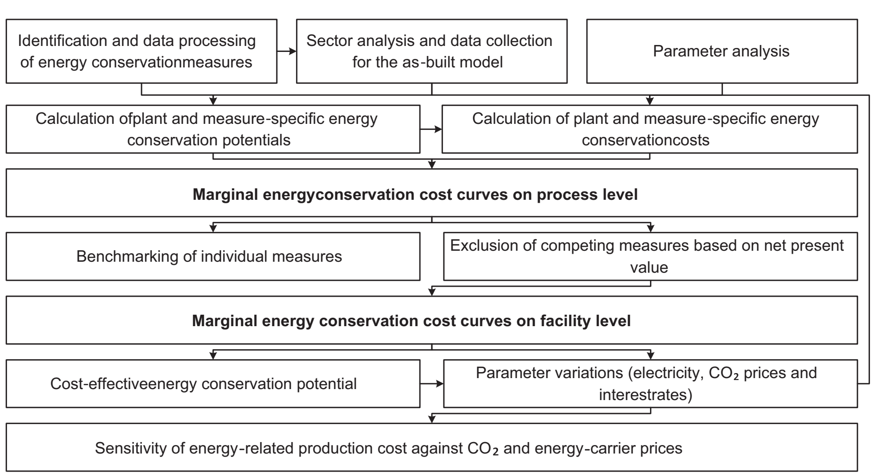


Fig. 3. Schematic overview of the methodology to calculate energy conservation cost curves.

conservations of measure k

$$\mathrm{MECC}_{k,r,m} = \frac{\sum_{i \in N} \mathrm{NPV}_{k,i} \times \mathrm{ANF}_{r,m}}{\mathrm{ESav}_k}.$$

3. Energy conservation measures

In every energy conservation potential assessment, the underlying parameters for the individual measures have a crucial impact on the final conservation potential. Thus, a detailed and exhaustive list of the parameters is provided in Table 1. A listing of consistent data on specific energy conservations and costs for measures applicable to the iron and steel industry are available for the U.S.A. (cf. US-EPA, 2010), Japan (cf. NEDO, 2008) and China (cf. Hasanbeigi et al., 2013a). Schlomann et al. (2011) gives information about measures for the German iron and steel industry based on the outcome of a workshop with industry experts and provides a valid input for Table 1, but the energy conservations are not listed consistently, costs are not respected and just twelve of our 31 investigated measures are covered. In contrast to Hasanbeigi et al. (2013a) and US-EPA (2010), four measures of our investigation express their conservation potential in dependence on a plant-specific value (see Section 2.3.1). These measures show a “var.” in the respective fuel or electricity conservation column of Table 1 and shall be described briefly hereafter.

First, the measure “Extended COG recovery” with the ID “COKE1” enhances the present recovery rate of the energy-rich coke oven gas (COG). The conservation potential depends on the additional recovery which is the difference between the maximum 484 m^3 COG/t coke [3] and the present recovery rate ($X_{i,\mathrm{COKE1}}$) of an individual coke plant i. The total fuel conservation potential $\mathrm{ESav}_{\mathrm{COKE1}}$ for the three eligible German coke plants is calculated as

$$\mathrm{ESav}_{\mathrm{BF1}} = \sum_{i=1}^{16} ((0.25\ t\ \mathrm{coal}/t\ \mathrm{iron} - X_{i,\mathrm{BF1}}) \times 0.9\ t\ \mathrm{coke}/t\ \mathrm{coal} \times 3.45\ \ \mathrm{GJ}/t\ \mathrm{coke} \times \mathrm{Cap}_i)$$

whereby the heating value of COG (0.017412 $\mathrm{GJ/m^3}$) is based on Diemer et al. (2004) and Cap_i stands for the production capacity in tonnes of coke per year.

Second, the conservation potential of the measure “Extended Pulverised Coal Injection (PCI)” with the ID “BF1” is depending on the present injection rate ($X_{i,\mathrm{BF1}}$) of the individual blast furnace i. For each unit of injected coal, the production of 0.9 unit of coke is avoided (EIPPCB, 2010). While an injection rate of 180 kg/t iron can be seen as standard practice, maximal injection of rates between 250 and 280 kg/t iron are possible (cf. EIPPCB, 2010; Worrell et al., 2010; Ribbenhed et al., 2008; JCI, 2007). The actual energy conservations occur upstream in the coke plant and are therefore only attributable on facility-level investigations. The total fuel conservation potential $\mathrm{ESav}_{\mathrm{BF1}}$ is calculated as follows:

$$\mathrm{ESav}_{\mathrm{BF1}} = \sum_{i=1}^{16} \left(\left(0.25\ t \frac{\mathrm{coal}}{\mathrm{t}} \mathrm{iron} - X_{i,\mathrm{BF1}} \right) \times 0.9\ t\mathrm{coke}/t\mathrm{coal} \times 3.45\ \ \mathrm{GJ}/t\mathrm{coke} \times \mathrm{Cap}_i \right).$$

Further, the installation of new and more powerful transformers for the electric arc furnace (EAF3) lead to a reduced specific electricity consumption of 3.96 MJ/t crude steel for every MVA of additional power (Worrell et al., 2010). The total electricity conservation $\mathrm{ESav}_{\mathrm{EAF3}}$ for the measure “high-performance transformer” with an assumed maximum power of 205 MVA (cf. Hölling et al., 2011) are calculated as follows:

$$\mathrm{ESav}_{\mathrm{EAF3}} = \sum_{i=1}^{26} ((205\ \ \mathrm{MVA} - X_{i,\mathrm{EAF3}}) \times 0.00396\ \ \mathrm{GJ/MVA} \times \mathrm{Cap}_i).$$

Lastly, the average German steel works′ on-site power station has an efficiency of 30% (cf. Rubel et al., 2009). Therefore, a considerable conservation potential lies in the renewal of these on-site power plants and, subsequently, the improvement of the plant-specific efficiency $X_{i,KW1}$. The maximum efficiency for non-combined cycle power plants is assessed to be 40% (cf. Weishar, 2008; Bock and Schmidt, 2008) and the total conservations ESav_{PP1} are calculated with

$$\mathrm{ESav}_{PP1} = \sum_{i=1}^{3} \left((0.4 - X_{i,KW1}) \cdot \mathrm{Cap}_i / X_{i,KW1} \right).$$

For further description of the remaining measures, it is advised to consult the sources given in the respective column of Table 1.

4. Results

4.1. Fuel conservation cost curves

Following the methodology outlined in Section 2, the energy conversation cost curves are calculated by applying the identified energy conservation measures to each of the German steel works individually and by aggregating the individual potentials and costs afterwards. The fossil fuel and electricity conservations cost curves are displayed separately in order to respect the heterogeneity of these two sets of energy carriers in terms of exergy and price. It is further distinguished between the two system boundaries of this investigation as both boundaries hold different advantages (see Section 2.1). All following cost curves up to the sensitivity analysis (see Section 4.3) are based on the R15 scenario (see Table 2) which is defined with moderate electricity, fossil fuel and CO_2 price developments and an interest rate of 15%.

For a start, the fuel conservation cost curve (FCCC) on process level is considered (see Fig. 6). As outlined in Section 2.1, process boundaries are good for benchmarking measures. The major drawback, however, is that individual conservations cannot be added, so that the fuel conservation potential of the German iron and steel industry cannot be derived from the x-axis in Fig. 6. Fig. 6 gives instead a quick overview of the effectiveness of individual measures in terms of fuel conservations and costs. Basically, all measures left from the intercept are cost-effective, but their total economical effectiveness is unveiled first when both axes, the marginal costs on the y-axis and the energy conservations on the x-axis, are considered combined.

Therefore the size of the rectangle of each measure indicates its effectiveness. With the foresaid kept in mind, the most effective measures are the retrofit of regenerative burners in reheating furnaces at rolling mills (Mill4) and the heat recovery from blast furnace slag (BF4). Although slag heat recovery has been investigated since the late 80 s, a commercial application is still not available (cf. EIPPCB, 2010; Xie, 2010). Despite the challenges that are involved with this measure (e.g. a low heat transfer coefficient), the results underline that further research is worthwhile.

The following cost-effective measures relate to the rolling mill. With reference to the results of Arens et al. (2012) which could identify a constant reduction of the energy intensity over the last two decades in rolling operations, plus the increasing presence of near net shape casting measures (CC1 and CC2), we conclude that the trend of decreasing energy intensity in rolling operations will continue. The Top Gas Recovery Blast Furnace (BF5), which is proposed by the ULCOS consortium as one of four technologies with the overall aim to cut the specific CO_2 emissions of steel

[3] The maximum COG recovery rate is calculated based on the Schwelgern coke plant (cf. Liszio 2003) built in 2003 and the coke plant at Hüttenwerke Krupp Mannesmann with an assumed utilisation rate of 90%.

Table 2
Cost-effective fuel, electricity and process-related CO_2 conservation potentials at facility level for the German iron and steel industry in the period 2013–2035 and in relation to varying interest rates, CO_2 and electricity prices.

Scenario	Interest rate (%)	CO_2 price	Electricity price	Cost-effective fuel saving potential [PJ p. a.]	Cost-effective electricity saving potential [PJ p. a.]	Cost-effective process-related CO_2 abatement potential [Mt CO_2]
R30	30	Moderate	Moderate	28.92	17.69	1.32
R15[a]	15	Moderate	Moderate	92.74	17.69	7.39
R03	3	Moderate	Moderate	**109.60**	20.42	8.81
R15CO_2	15	High	Moderate	91.61	17.69	16.18
R15El	15	Moderate	High	80.53	**24.52**	6.37
R15CO_2El	15	High	High	97.62	23.33	**16.51**

[a] R15 holds as the base scenario and is used in fuel and electricity conservation cost curves discussion.

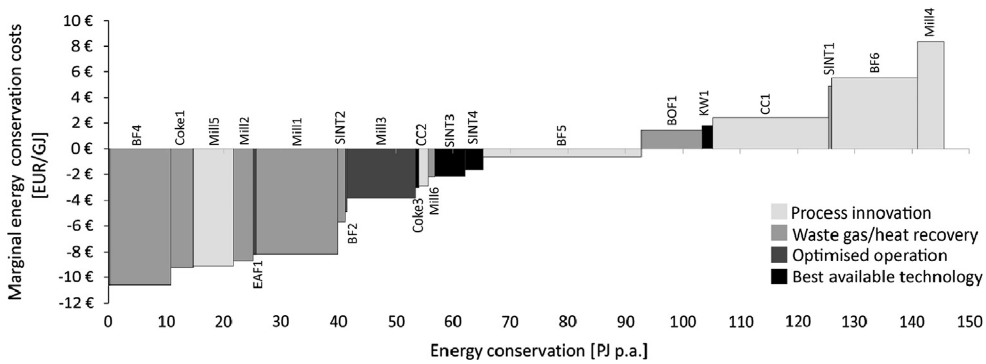


Fig. 6. Fuel conservation cost curve on process level for the period 2013–2035 with an interest rate of 15%, moderate fuel, electricity and carbon price developments. The process perspective is used to benchmark the individual measures. The *x*-axis displays the fuel conservations for each measure but not the total fuel conservation potential of the German iron and steel industry.

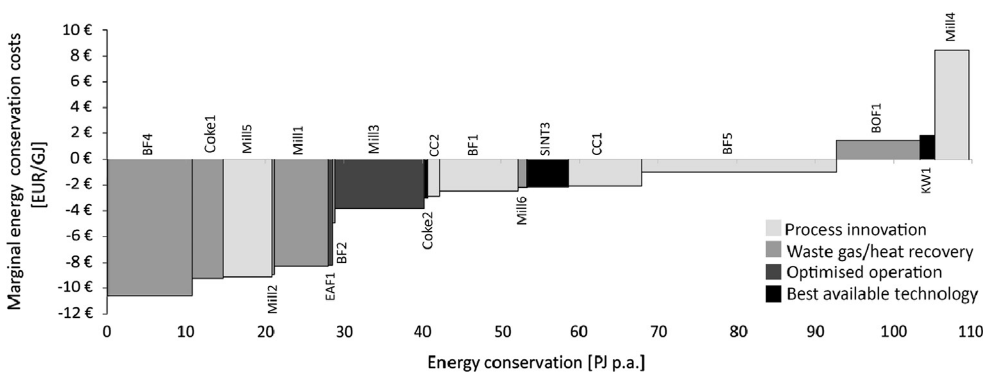


Fig. 7. Fuel conservation cost curve on facility level for the period 2013–2035 with an interest rate of 15%, moderate fuel, electricity and carbon price developments. On facility level, competing measures are excluded according to their net present value. The *x*-axis displays the total fuel conservation potential of the German iron and steel industry.

production by half (cf. Meijer et al., 2009), has with 27.57 PJ the highest fuel conservation potential but achieves only a moderate effectiveness. Being located in the top third of the total effectiveness ranking, still six more measures (i.e. Mill1, BF4, Mill5, Mill3, Coke1 and Mill2) are more effective than it.

The thin slab casting (CC2), which is believed to have a promising impact on the reduction of the energy intensity (cf. Dahlmann et al., 2012, 2010), has the second biggest fuel conservation potential but is accompanied with high capital costs which shifts, in combination with a large number of recently modernised rolling mills, the measure to the non-cost-effective part of the cost curve. In contrast to the process level, CC1 and CC2 become cost-effective on facility level (see Fig. 7). Here, both measures have to compete with all measures affecting the hot rolling operations (see Table 1) as the energy reduction from near net shape castings mainly result from a reduced rolling need. Following the methodology presented in Section 2.3, CC1 is only applied to plants where its NPV is higher than the combined NPV of the measures Mill1 to Mill7 at the same facility. In this way, the fuel conservation potential of CC1 – and the potential of the measures Mill1 to Mill7 likewise – is reduced, while its total cost-effectiveness is increased. The comparison of the two cost curves unveils that all competing measures experienced not only a left shift, but also a change in the ascending order of the measures in the cost curve. In some cases, a measure is always superior in terms of cost-effectiveness to its competing measures which lead to an exclusion of the inferior measures from the cost curve. For instance, the extension of the pulverised coal injection (BF1) is – in the base scenario – always more cost-effective than the usage of biochar as a reduction agent (BF6) due to its cost-intensive production. Same counts for the partial gas recirculation (SINT3) which achieves a higher NPV in all sinter plants than any other sinter measures. Finally, the total fuel conservation potential can be taken from the *x*-axis and added up to 92.74 PJ per year which is in relative figures 11.7% of the final energy use for the German steel production in the year 2010 (cf. VDEh, 2012).

Besides the fuel consumption, the effect on the fossil fuel and process-related CO_2 emissions is respected for the cost calculation

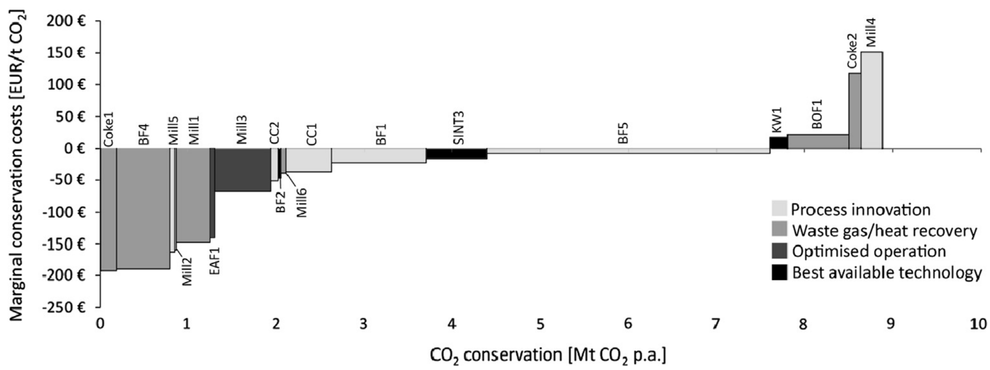


Fig. 8. CO_2 abatement cost curve on facility level for the period 2013–2035 with an interest rate of 15%, moderate fuel, electricity and carbon price developments. On facility level, competing measures are excluded according to their net present value. The *x*-axis displays the total CO_2 abatement potential of the German iron and steel industry.

(see Section 2.3.2). So, although the focus of this article lays on the energy conservation, Fig. 8 gives an overview of the CO_2 abatement potential of the investigated measures. The cost-effective abatement potential is 7.39 Mt of CO_2 per year which is expressed in relative figures 12.2% of total CO_2 emissions that were accompanied with the production of steel in the year 2010 (cf. VDEh, 2012). Nearly 50% (3.21 Mt CO_2 p. a.) of the cost-effective abatement potential is caused by the Top Gas Recovery Blast Furnace (BF5) which makes this measure the most effective single measure from a CO_2 perspective. Without economic aspects, however, the most effective single CO_2 abatement measure is the utilisation of CO_2-neutral biochar (BF6) which would lead to an annual reduction of 10.09 Mt CO_2, but is, due to its high production costs, inferior at all plants to its competing measure BF1 and therefore not listed on facility level.

4.2. Electricity conservation cost curves

The results of the electricity conservation are discussed separately from the other energy carriers in order to respect its higher price and exergy. In general, fewer measures are investigated in the electricity conservation cost curve (ECCC) than in the FCCC. As a matter of course, the majority of these measures address the electric steel route in particular. Analogously to the results of fuel-related measures, the discussion of the FCCC on process level is followed by the results on facility level. The results on process level are used to assess the effectiveness of the individual measures (see Fig. 9). The installations of new and more powerful transformers (EAF3) result in the highest effectiveness and with 5.87 PJ p. a. in the highest individual electricity conservations. The second most effective measure is the continuous charging and scarp preheating (EAF6) which would conserve 3.23 PJ p. a. A commercial realisation of this measure (Consteel® by Tenova) has been implemented in 39 plants worldwide (cf. Memoli et al., 2012). In Germany, this measure was adopted at the Trierer Stahlwerke GmbH (cf. Memoli et al., 2009), but unfortunately the mini mill is currently closed. However, the effectiveness indicates that considering this measure in the discussion about energy efficiency is still worthwhile. Same counts for the Direct Current Electric Arc Furnace (EAF4) which is currently implemented in three German mini mills (cf. Fandrich et al., 2009) and hold a prospective conservation potential of 3.32 PJ p. a. Another promising measure is the recovery of the blast furnace's top gas pressure with a turbine (BF3) which achieved the fifth place in the effectiveness ranking. Differing from the results of Arens et al. (2012), our research shows that only eight out of 16 blast furnaces are equipped with turbines so far which is backed up by Dahlmann et al. (2010). Considering the technical requirements (see Table 1), the remaining potential at six blast furnace could lead to a conservation of electricity of 2.19 PJ p. a. One measure that has been controversially discussed is Coke Dry Quenching (CDQ) (cf. Liszio et al., 2012). Like all other measures that recover an intermediate (e.g. steam) for sole electricity generation purposes, the energy conservations are valued as electricity and weighted with the average efficiency of the German steel works' on-site power plants (30% Rubel et al., 2009). CDQ (Coke2), when adopted to all five German coke plants, could lead to electricity conservations of 5.34 PJ per year, but the combination of high capital costs, additional maintenance costs (see Table 1) and comparatively new coke plants (e.g. Liszio, 2003) result in total to specific conservation costs of 7.31 EUR/GJ.

On facility level (see Fig. 10), CDQ is competing with Coke Stabilization Quenching (CSQ) which is, due to the much lower capital costs, superior in terms of cost-effectiveness, but hardly achieves any energy conservation effect (cf. EIPPCB, 2010). Still, the high electricity conservation potential and high adoption rate of CDQ in Japan (cf. Schlomann et al., 2011) and China (cf. IEA, 2007) facilitate the importance of this measure in the discussion about energy efficiency in the iron and steel industry. Moreover, with rising electricity prices CDQ becomes more economical. In fact, the results indicate that starting from 0.108 EUR/kW h CDQ becomes cost-effective at all five German coke plants (see Section 4.3).

Measures on facility level that are excluded from the cost curve by more cost-effective measures are continuous operation and heat recovery with Arccess Steady EAF (EAF8) and waste heat recovery from exhaust gas (SINT2) at the sinter plant. Analogously to the results of the FCCC, the facility boundaries are needed to assess the total energy conservation potential which is 17.69 PJ or in relative figures: 2.2% of the industry's final energy use (cf. VDEh, 2012) or 22.9% of the final electricity use (cf. DESTATIS, 2010) in the year 2010.

4.3. Sensitivity analysis

4.3.1. Parameter variations

The German Federal Environment Office (UBA) recommends an interest rate of 3% for the economical assessment of environmental damages with a period up to 20 years (UBA, 2007). This, however, hardly reflects common guidelines of companies for assessing the feasibility of major projects. For instance, ArcelorMittal demands an internal rate of return (IRR) of 15% for a demonstration project of the new TGRBF (see Table 1) at ArcelorMittal Eisenhüttenstadt GmbH. The 15% is based on weighted average cost of capital (WACC) of 10%, plus an additional interest rate risk of 4.5% (EC, 2010). Although an interest rate of 15% is widely used for assessing cost-effective energy conservation potentials in the industry sector (cf. Hasanbeigi et al., 2013a; Fleiter, 2012; Beer et al., 2009), it needs to be noted that still the majority of companies demands

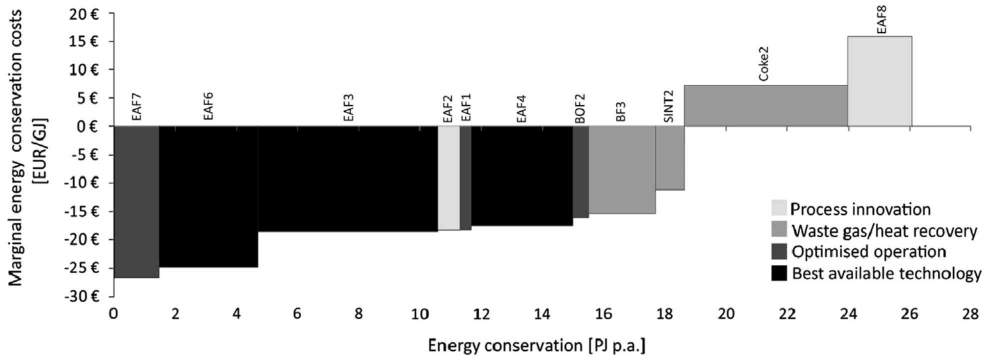


Fig. 9. Electricity conservation cost curve on process level for the period 2013–2035 with an interest rate of 15%, moderate fuel, electricity and carbon price developments. The process perspective is used to benchmark the individual measures. The *x*-axis displays the electricity conservations for each measure but not the total electricity conservation potential of the German iron and steel industry.

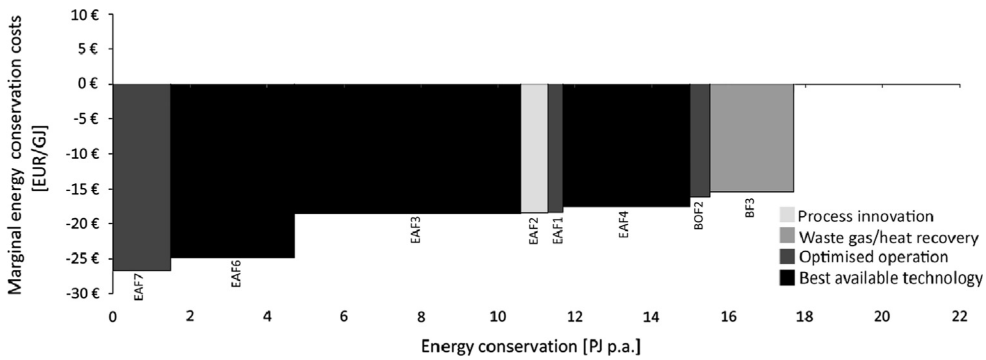


Fig. 10. Electricity conservation cost curve on facility level for the period 2013–2035 with an interest rate of 15%, moderate fuel, electricity and carbon price developments. On facility level, competing measures are excluded according to their net present value. The *x*-axis displays the total electricity conservation potential of the German iron and steel industry.

a payback time less than two years when investing in energy efficiency measures (cf. Fleiter, 2012; Hölling et al., 2011; Trygg et al., 2010). This fact itself is a major barrier in the energy efficiency discussion (cf. Pardo and Moya, 2013; Fleiter et al., 2011) but not in the scope of this paper. In general, a project with an IRR of 15% can be more or less compared to a payback time of five years with a life time of ten years (cf. Beer et al., 2009). So in order to reflect the industry's preference for short payback periods (Sathaye et al., 2011), an IRR of 30% (equivalent to a payback time of three years with a life time of ten years) is additionally respected in the sensitivity analysis.

The expenditure on electricity has a considerable impact on the total production costs, in particular for the electric arc furnace route. Steel mills therefore tend to hedge electricity prices years ahead in order to minimise risks. The acquired electricity price is business-critical and kept secret as otherwise competitors could calculate the respective profit margin. Consequently, detailed information about electricity prices at mill level are hard to find. Bruce et al. (2010) is calculating with electricity price of 0.06 EUR/kW h for an average steel mill in Europe in the year 2010. Seefeld and Claaßen (2011) gives more detailed numbers for Germany: The average steel mill in 2010 had to pay 0.0671 EUR for a kW h which is expected to increase up to 0.081 EUR/kW h until 2020. This development is used as the basis for the moderate electricity price scenario and updated with the projection of Fahl et al. (2010) until the year 2035 (see Fig. 11). The electricity price development of Blesl et al. (2011) which respects Germany's nuclear power phase-out holds as the basis for the high electricity price scenario (R15El, see Table 2). The CO_2 certificate price projection in the moderate scenario is similar to fuel price projections (see Section 2.1) based on Schlomann et al. (2011). For the high CO_2 price scenario (R15CO_2) Blesl et al. (2011) is consulted again. The CO_2

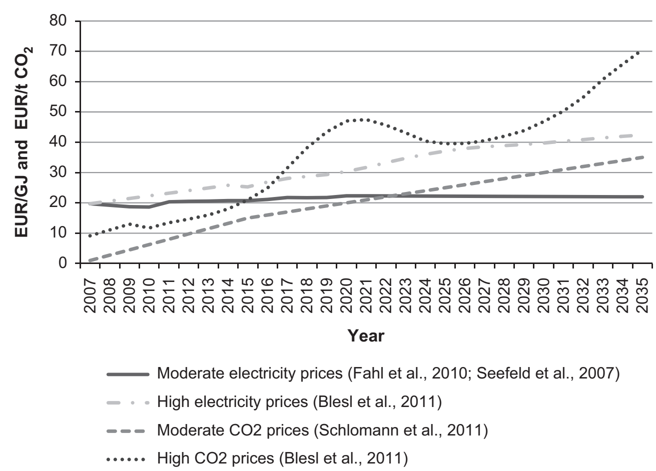


Fig. 11. Moderate and high electricity and CO_2 price developments which are used in the scenarios.

price was selected for the parameter variation due to the fact that CO_2 certificates can be more or less comprehended as a fuel price increment. Consequently, measures that lead to fuel conservations are more favoured in this case. So rather than raising the price of thirteen different fuel types, the price of CO_2 certificates is raised. It needs to be noted that an increase of CO_2 prices has an effect on all energy systems that are covered by the European Union Emission Trading Scheme (EU ETS) which also includes electricity suppliers. According to Reinaud (2004), a carbon price of 30 EUR/t CO_2 could lead to an increase in electricity prices of 32%. The last scenario of Table 2 respects this effect by combining the high carbon price scenario with the high electricity price scenario.

4.3.2. Effects on the cost-effective conservation potentials

Table 1 shows the cost-effective fuel, electricity and conservation potentials at facility level with varying interest rates, electricity and CO_2 certificate prices. Unsurprisingly, the highest correlation (-0.95) between parameter and cost-effective conservation potential holds the interest rate. Between the lowest (R03) and highest interest rate (R30), the cost-effective fuel conservation potential triples from 28.9 to 109.6 PJ p. a. The results underline that risk-averse investment criteria, such as high internal rates of return ($>15\%$) or short payback times (<3 years), are a major barrier to energy efficiency (cf. Pardo and Moya, 2013; Fleiter et al., 2011).

The second strongest effect, with a correlation coefficient of 0.89, can be found between the electricity prices and the cost-effective electricity conservation potential. In the high price scenario (R15El), all investigated electricity conservation measures become cost-effective and increase the cost-effective potential by 6.83 PJ p. a. of which 5.34 PJ is solely owed to Coke2. However, the cost-effective fuel conservation potential is reduced by 12.21 PJ p. a. as more and more electricity-focused conversation measures are replacing measures that are primarily conserving fuel. In contrast, higher electricity prices have no effect at all on the cost-effective fuel conservation potential.

The third highest correlation (0.83) is found between the CO_2 certificates prices and the cost-effective conservation potential of fuel and process-related CO_2 emissions (see Table 2). Between the moderate (R15) and high carbon prices scenario (R15CO_2), the conservation potential of process related CO_2 emissions is almost doubled, from 8.81 Mt CO_2 to 16.18 Mt CO_2 p. a., whilst having more or less identical electricity and fuel conservation potentials. This can be explained by competing measures that have a great process-related CO_2 abatement potential, but comparatively low energy conservation potential such as using biochar (BF6) as a reducing agent in the blast furnace (see Table 1). These measures are achieving in R15CO_2 higher NPVs and replacing sole fuel conservation measures like BF1. In contrast to the electricity conservation potential, the highest CO_2 abatement potential, 16.51 Mt CO_2 p. a., is obtained with high electricity and carbon prices (R15CO_2El) and not in R15CO_2.

Overall, it needs to be noted that the total conservation potential is depending on the amount and kind of investigated measures. For instance, including sole CO_2 emission abating measures (e.g. CCS) in the investigation will consequently increase the CO_2 abatement potential.

4.3.3. Effects on the specific energy and CO_2 emission costs

In this chapter, the increased costs for fuel, electricity and CO_2 certificates are put in relation to the specific cost-effective conservation potentials in order to reflect the effects on the steel production costs in Germany. The total production costs can be divided into fixed and variable costs whereas the latter basically consists of the costs for raw materials, energy and CO_2 allowances. Although there are some examples for the cost structure of steel mills available (e.g. Reinaud, 2004), this analysis is focused only on the energy and carbon costs in order to avoid additional data uncertainties. Still, it is expected that the analysed costs are sufficient to indicate the risk of carbon leakage and other relocation effects. For the calculation of energy and carbon costs, consistent data of the specific energy consumption and CO_2 emissions of the different processes is needed. Based on Table 3 and the fuel, electricity and carbon prices (see Fig. 2), an energy cost structure for each production step is calculated for the year 2013 as a reference point (see Table 4).

It needs to be noted that the absolute cost figures from Table 4 might not represent the actual specific energy-related production costs of a real steel mill as some model values (e.g. the carbon price for the year 2013) are not in line with the actual market price for the same year because the focus of this article lays rather on their development until 2035. Besides, deriving reliable and plant-specific production cost structures are from a scientific point of view very difficult. The results of the further analysis are therefore given in relative numbers in order to circumvent this issue. These relative costs are calculated for all scenarios with an interest rate of 15% (R15). In the cost calculations, not only increasing energy and carbon prices are considered, but also the dynamic effects that are evolving from the adoption of cost-effective energy conservation measures on the production cost are respected. As Table 2 demonstrates with rising energy and carbon prices are more measures becoming cost-effective. This self-amplifying effect can compensate for rising energy prices.

Fig. 12 shows the average energy-related production costs in the period 2013–2035 in relation to Table 4 with (+EC) and without the cost reduction effect of energy conservation measures. In the base scenario (R15), the electrical steel producer has to cope with 13%, oxygen steel producer with even 30%, higher specific energy-related production costs, because the doubling of the average CO_2 price has a stronger impact on the fossil fuel based oxygen route compared to the electrical route. Plus, the electricity price increases only marginally in the base scenario (see Fig. 11). Through the adoption of cost-effective energy conservation measures, the cost increase can be reduced to 6%. In case of the electrical route, the energy conservation effect can even overshoot

Table 3
Specific energy consumption and CO_2 emissions for each steel production process of the German iron and steel industry in the year 2010.

Specific energy consumption [GJ/t crude steel]	Sinter plant [a]	Coke plant [f]	Blast furnace	BOF	EAF	Casting and rolling
Total fuel	0.92	1.78	11.66	0.06 [b]	0.88	1.99
Coal	0.87	0.56 [c]	2.97		0.13	
Natural gas	0.05	1.22 [c]	0.29	0.06	0.75	1.36
Coke			8.11			
Fuel oil			0.29			
COG						0.32
BFG						0.31
Electricity	0.06	0.03 [d]	0.54	0.14	2.03	0.62
CO_2 emissions [e] [t CO_2/t crude steel]	0.09	0.12 [c]	1.37	0.00	0.05	0.12

The values of specific final energy consumption are based on Ghenda (2011).

[a] The specific energy consumption [GJ/t sinter] from Ghenda (2011) is converted with factor 0.589 [t iron/t sinter].

[b] Value is for German BOF plants in the year 2007 (cf. Arens et al., 2012).

[c] Average value for the EU-27 (cf. Liszio et al., 2012).

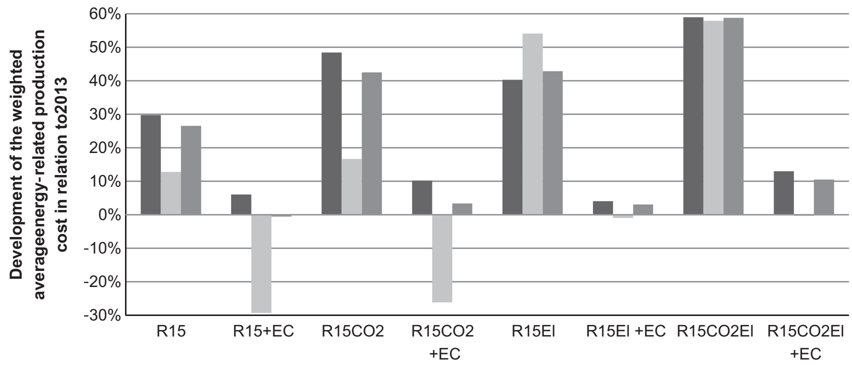
[d] World best practice value for coke plants (cf. Worrell et al., 2008).

[e] Covers only fuel-related CO_2 emissions. The specific CO_2 emissions that used for the calculation are: 0.0946 t CO_2/ GJ coal, 0.0561 t CO_2/GJ natural gas, 0.129 t CO_2/ GJ coke, 0.0774 t CO_2/GJ fuel oil (cf. Quaschning, 2011), 0.048 t CO_2/GJ COG (cf. Bender et al., 2008) and 0.105 t CO_2/GJ BFG (cf. UBA, 2003).

[f] The specific energy consumption [GJ/t coke] from Ghenda (2011) is converted with factor 0.348 [t iron/t coke].

Table 4
Specific energy-related production costs for each steel production process of the German iron and steel industry for the year 2013. The costs are based on the specific energy consumption from Table 3.

Specific energy-related cost [EUR_{2013}/t crude steel]	Sinter plant	Coke plant	Blast furnace	BOF	EAF	Casting and rolling
Total energy-related cost	6.59	15.63	109.82	3.44	49.88	31.34
Fuel	4.41	13.52	82.99	0.56	7.38	17.12
Electricity	1.20	0.72	11.12	2.84	41.87	12.79
CO_2 certificates	0.98	1.39	15.71	0.04	0.63	1.43



	R15	R15+EC	R15CO2	R15CO2 +EC	R15El	R15El +EC	R15CO2El	R15CO2El +EC
BOF route	30%	6%	48%	10%	40%	4%	59%	13%
EAF route	13%	-29%	17%	-26%	54%	-1%	58%	0%
Total	27%	-1%	43%	3%	43%	3%	59%	11%

Fig. 12. Weighted average effects on the specific energy-related production costs of the German iron and steel industry in the period 2013–2035, without and with energy conservation (+EC), for the two major steel production routes and the total production in relation to the year 2013. (For the calculation of the underlying absolute energy-related costs were the average energy and carbon prices from 2013 to 2035 of the respective scenario used. The different energy-intensities (see Table 3), energy costs (see Table 4) of the processes and the installed capacity share (68% oxygen steel) of the two major production routes are used as weighting factors.).

the rising prices and reduce the energy-related costs by −29%. For the total effect on the German steel production, the results of each route are weighted with the model′s annual production capacity (68% share for oxygen steel). In the scenario R15CO_2, the average carbon price is quadrupled which leads to an energy-related production costs increase by 48% in the oxygen route while the EAF route is with its low carbon costs (see Table 4) hardly affected. The reverse situation emerges when the average electricity price is increased by more than a 57% (R15El). In both scenarios, the total average energy-related costs are increased by 43% and energy conservation measures can suppress the cost increment to 3%. A closer look on the two major productions routes unveils that the increase of electricity or carbon prices, respectively, have different impacts on the respective energy-related production costs. For instance, it is appealing that the compensation ability of the EAF route is significant higher than of the BF/BOF route. Even with both, high electricity and carbon prices (R15CO_2EL), the energy conversation can fully compensate the rising prices while integrated steel producers have to cope with in average 13% higher energy-related production costs. This is interesting, as for instance the CO_2 abatement cost-curve (see Fig. 7) shows that the EAF route has no significant CO_2 abatement potentials. The EAF route profits from two facts: First, there is a considerable untouched electrical conservation potential (see Fig. 10) that can compensate the increased electrical price. Second, due to its low specific CO_2 emissions (see Table 3), the route is hardly affected by increasing carbon prices. Although the production capacity is fixed to individual plants and energy conversations from process substitution are not in the scope of this paper, the results indicate strongly that a prospective change in the German steel production capacity to the advantage of the EAF route is likely to happen.

At the bottom line, the cost-effective energy conservation potentials can considerably alleviate rising energy and carbon prices which mitigates – provided all cost-effective measures will be adopted – the risk of relocation. However, while the EAF route can overcompensate rising prices, the BOF route will have to face increased energy-related production costs by 6 to 13% which indicates a higher relocation risk for this route in particular. It needs to be noted that the production factors of countries which are not covered by the EU ETS affect the relocation risk as well. Moreover, the steel industry often refers to their long-lasting partnerships with clients and a quick, flexible and responsive logistic as factors that speak for Germany as a production location. It is further important to note that the results are derived on the basis of a complete diffusion of all cost-effective identified measures. The applicability of each measure has been thoroughly checked for each plant, so that the described final energy conservations should be achieved when barriers are not considered.

5. Concluding discussion

We developed energy conservation cost curves for the German iron and steel industry in the period 2013–2035 and performed a sensitivity analysis to investigate the effects on the cost-effective energy conservation potential and on the energy and carbon costs. It was stressed throughout the article, that the results of any energy conservation potential assessment depends on the defined system boundary and the calculation method which were both explained thoroughly to facilitate the comprehensibility and transferability of the results.

The investigation was carried out with two system boundaries as they both held different advantages: the process boundary was used for benchmarking individual measures while the facility boundary was used for the calculation of the industry′s total conservation potential. High detailed plant-specific data was available for the investigation which implied the development of new calculation method. The developed method respects, among others, the current efficiency of the individual plants. Another crucial impact on the results was attributed to the parameters of the investigated measures. A detailed table with consistent data for energy conservations measures applicable to German steel works for the year 2013 was listed.

In order to respect the higher exergy and price of electricity in contrast to other energy carriers, the investigated 32 measures were analysed accordingly in two curves, namely the fuel (FCCC) and the electricity conservation cost curves (ECCC). The FCCC on process level unveiled that a considerable amount of measures related to the rolling mills were cost-effective and that the so far observed trend of decreasing energy-intensity in hot rolling operations was likely to progress. Only a moderate effectiveness but the second highest CO_2 abatement potential could be achieved by the Top Gas Recovery Blast Furnace (TGRBF) without CCS (BF5). Our results showed that the TGRBF without CCS alone was by far not capable to achieve the 50% CO_2 reduction goal of ULCOS. Based on the low cost-effectiveness of the TGRBF without CCS and the additional costs for CO_2 sequestration, we further assume that the TGRBF with CCS will not be cost-effective with the given carbon prices.

It was surprising to see that the promising measure thin slab casting (CC2), despite its huge specific energy conservations, was not cost-effective at half of the steel works due to the combination of high capital expenditure and recently modernised casting plants. In terms of electricity conservation, most measures affected the electric arc furnace. The most effective measures identified were the installation of new and more powerful transformers (EAF3), continuous charging and scarp preheating (EAF6) and direct current electric arc furnace (EAF4). A considerable electricity conservation potential held the equipment of the remaining blast furnaces with top gas recovery turbines (BF3). Lastly, the results showed that measures that have been controversially discussed over the last decades (e.g. heat recovery from blast furnace slag (BF4) or Coke Dry Quenching (Coke2)) were worthwhile to be still considered in the energy efficiency debate.

On facility level, competing measures were sorted out according to their plant-specific NPV. The resulting cost curves were used to assess the total conservation potential of the sector. In the base scenario, the cost-effective energy conservation potential was assessed to be 110.43 PJ or 13.9% of the industry sector's final energy use in the year 2010. However, we like to note that our investigation was carried out ceteris paribus. For instance, the production capacity and the demand of different steel products was constant which limited, among other, the adoption potential of energy conservation measures that are restricted to certain kinds of steel products.

In the following sensitivity analysis the price for CO_2 certificates, the electricity price and the interest rate were varied and their effects on cost-effective conservation potential were analysed. Unsurprisingly, using low interest rates in investment decisions had the strongest positive effect on the cost-effective energy conservation potential. This result confirmed that the companies' preference for short payback times inhibits the adoption of energy conservation measures. The sensitivity analysis showed further that on the one hand, high electricity prices increased the cost-effective electricity conservation potential, but, on the other hand, led to reduced fuel and carbon conservation potentials. High carbon prices resulted in a doubling of the cost-effective CO_2 abatement potential while at the same time the energy conservation potential slightly decreased. The highest combined potential with moderate interest rates was obtained when both electricity and carbon prices were raised.

In the further analysis, the effects on the energy-related costs of the steel production were investigated. The results were given in relation to the base scenario in the year 2013 and indicated that the cost-effective energy conservation potentials could considerably compensate rising energy and carbon prices which mitigated – provided all cost-effective measures were adopted – the risk of relocation. In terms of the two production routes: The EAF route could even compensate high electricity prices while the BOF route showed a moderate sensitivity for rising carbon prices which led to net increase of energy-related production costs by 6 to 13% and indicated a higher relocation risk for this route in particular. Consequently, one-to-one applications of energy reduction goals to the iron and steel sector would lead to unequally distributed burdens as the specific energy conservation costs differs among the steel works. The high sensitivity against interest rates shows that the right conditions (e.g. long-cycles between policy changes) need to be established so that companies are able to benefit from long-term investments in energy efficiency.

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